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THERMOGRAVIMETRIC ANALYSIS OF SOLID REFUSE-DERIVED FUELS AND CO--ETC(U)
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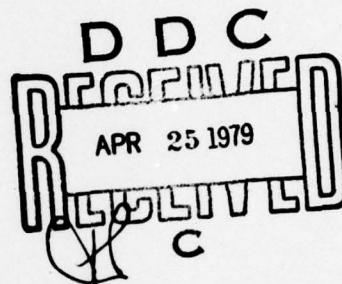
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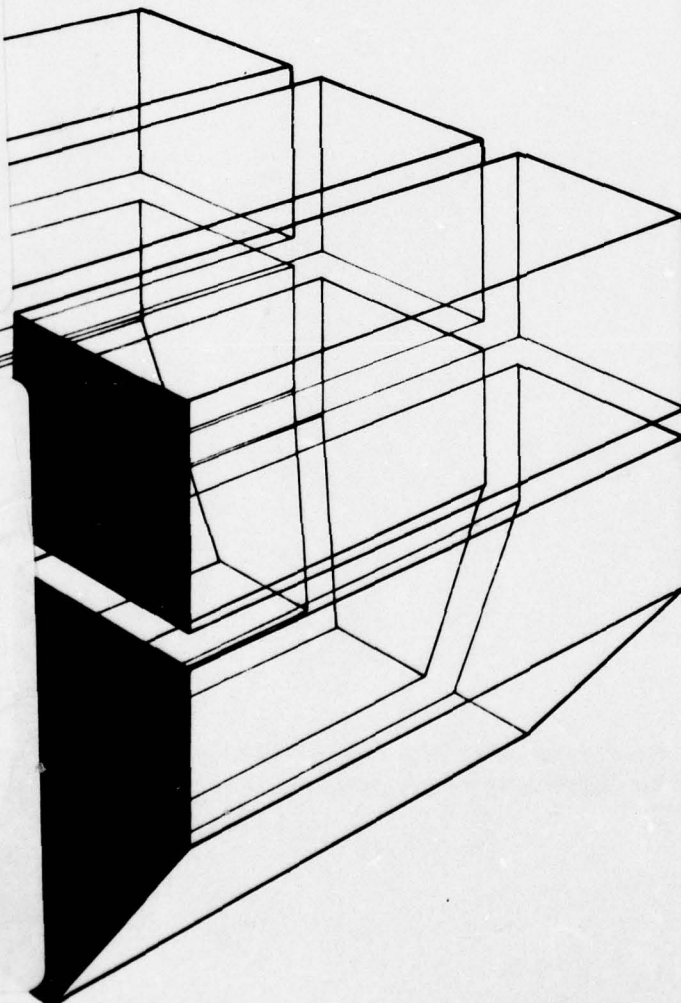
THERMOGRAVIMETRIC ANALYSIS OF SOLID
REFUSE-DERIVED FUELS AND COAL

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by
S.A. Hathaway
J.S. Lin

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The ignition and combustion rates of three types of densified refuse-derived fuel (DRDF) and low-volatile Illinois bituminous coal were investigated at temperatures ranging from 600°C to 1000°C and residence times ranging up to 120 sec. It was found that DRDF ignition time is up to 12 times less than that of coal, that the temperature required for coal ignition at a given residence time is greater than that needed for DRDF ignition, and that the DRDF:coal time to ignition ratio is expressible as a linear function of furnace temperature. It was also		

Block 20 continued.

→ found that DRDF produced from mixed municipal-residential solid waste has a slower combustion rate than that produced from homogeneous heavy paper stock, and that the combustion rates of all types of DRDF are significantly greater than that of the coal tested at a 99.9 percent level of confidence.

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FOREWORD

This research was performed for the Directorate of Military Programs, Office of the Chief of Engineers (OCE), Department of the Army, by the U.S. Army Construction Engineering Research Laboratory (CERL) under Program Element 6.11.02A, "Basic Research"; Project Number 4A761102AT23, "Basic Research in Military Construction"; Task A2, "Energy Systems"; Work Unit 011, "Combustion Properties of Refuse-Derived Fuels." The OCE Technical Monitor was Mr. B. Wasserman, DAEN-MPO-U. Mr. S. Hathaway of the CERL Energy and Habitability Division (CERL-EH) was the Principal Investigator.

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COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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THERMOGRAVIMETRIC ANALYSIS OF SOLID REFUSE-DERIVED FUELS AND COAL

1 INTRODUCTION

Background

Numerous studies have indicated the potential for using solid-phase, densified, refuse-derived fuel (DRDF) as a coal supplement in military-scale central heating and power plants equipped with mechanical stokers.¹⁻⁷ Although several short-term tests cofiring DRDF and coal have been conducted, few data have been collected that indicate what furnace modifications are required to maintain rated capacity through a boiler's projected functional life, while using economic quantities of DRDF.⁸⁻¹⁰

- 1 S. A. Hathaway and R. J. Dealy, Technology Evaluation of Army-Scale Waste-to-Energy Systems, Interim Report E-110/ADA042578 (U.S. Army Construction Engineering Research Laboratory [CERL], July 1977).
- 2 A. J. Buonicore and J. P. Waltz, District Heating with Refuse-Derived Fuel at Wright-Patterson Air Force Base (Wright-Patterson Air Force Base, September 1975).
- 3 P. Kong, M. Lee, and S. A. Hathaway, Fuels: State of the Art in Industrial Utilization, Technical Report E-135/ADA063239 (CERL, August 1978).
- 4 S. A. Hathaway, Recovery of Energy From Solid Waste at Army Installations, Technical Manuscript E-118/ADA044814 (CERL, August 1977).
- 5 H. I. Hollander, Processed Refuse: A Salvage Fuel for Existing Boilers (Gilbert Associates, 1977).
- 6 H. G. Rigo, S. A. Hathaway, and F. C. Hildebrand, Preparation and Use of Refuse-Derived Fuels in Industrial Scale Applications, Conference Papers of First International Conference and Technical Exhibition on Conversion of Refuse to Energy, New York (1976).
- 7 The Feasibility of Resource Recovery of Federal Solid Waste in the Washington, D.C. SMSA (National Center for Resource Recovery, 1978).
- 8 CAPT J. W. Jackson, A Bioenvironmental Study of Emissions from Refuse-Derived Fuel, USAF Environmental Health Laboratory Report 76M-2 (McClellan AFB, 1976).
- 9 Solid Waste Fuel Modifications: Second Series Burn Tests - Final Report (Eugene Water & Electric Board, 1974).
- 10 A Field Test Using Coal:d-RDF Blends in Spreader Stoker Fired Boilers (Systems Technology Corp., 1978).

Claims that DRDF burns similarly to coal imply that no furnace modifications are necessary and lead to the conclusion that an inexpensive fuel supplement can be used with little or no capital cost and operating adjustments.¹¹ Conversely, other work in industrial-scale fuel substitution suggests that substantial furnace modifications, at proportional costs, are required if DRDF is to be cofired in coal-designed boilers.¹²⁻¹⁵ The latter claim is supported by the fact that DRDF contains a great deal of cellulose and therefore has a different chemistry from coal, which is more parafinic; thus, it can be expected to behave differently in high-temperature furnace environments.¹⁶⁻¹⁸

Work in determining the combustion properties of simulated and shredded municipal refuse and separate investigations into the reactivity and gasification characteristics of high-cellulose waste materials have shown that combustion rate is one key factor in determining the efficacy of using waste fuels such as DRDF in furnaces designed for conventional fossil fuels.^{19,20} The design and performance impacts of cofiring low- and high-reactivity fuels in a vessel designed exclusively

- 11 A Field Test Using Coal:drdf Blends in Spreader Stoker Fired Boilers.
- 12 A. Frendberg, Performance Characteristics of Existing Utility Boilers When Fired with Low-Btu Gas (Babcock and Wilcox Co., 1974).
- 13 C. L. Richards, "Conversion to Coal - Fact or Fiction?" *Combustion* (April 1978).
- 14 S. A. Hathaway and R. J. Dealy, Technology Evaluation of Army-Scale Waste-to-Energy Systems, Interim Report E-110/ADA042578 (CERL, July 1977).
- 15 E. M. Honig, Jr., and S. A. Hathaway, Application of Modern Coal Technologies to Military Facilities, Interim Report E-130/ADA055560 (CERL, May 1978).
- 16 Incinerator Overfire Mixing Demonstration (A. D. Little Co., 1975).
- 17 E. R. Kaiser, "Physical Character of Municipal Refuse," *Combustion* (February 1977).
- 18 S. A. Hathaway, Recovery of Energy From Solid Waste at Army Installations, Technical Manuscript E-118/ADA044814 (CERL, August 1977).
- 19 J. E. L. Rogers, Solid Fuel Combustion and Its Application to the Incineration of Solid Refuse, Sc.D. Thesis (Massachusetts Institute of Technology, 1973).
- 20 Reactivity and Gasification Characteristics of Low Ranking Coals and Potentially Reducing Waste Materials (Pittsburgh Energy Research Center Report PERC/RI-72/2, 1976).

for either have been shown to be potentially dramatic.^{21,22} While there is substantial information regarding the reactivity of North American coals, there are no similar data for DRDF.^{23,24}

This gap in design-related information creates considerable risk in implementing military-scale DRDF systems. Without furnace modification, using DRDF may result in boiler derating and consequent severe impacts on both the mission and economics of installation heating or power plant operations. Similarly, unnecessary furnace modifications to cofire DRDF would also result in financial loss.

Objective

The objective of this investigation was to compare the ignition and combustion rates of DRDF and coal.

Approach

This investigation was conducted in three steps:

1. Samples of DRDF and coal were acquired and their proximate and ultimate analyses and calorific values established.
2. The samples were tested in a muffle furnace at temperatures ranging from 600°C to 1000°C in increments of 100°C to determine time to ignition and combustion rates.
3. Burning profiles were tested statistically to determine if there were significant differences between the DRDF and coal samples.

²¹ S. A. Hathaway and R. J. Dealy, Technology Evaluation of Army-Scale Waste-to-Energy Systems, Interim Report E-110/ADA042578 (CERL, July 1977).

²² R. J. Williams, Coal and Refuse Combustion for Efficient Utilization (Riley Stoker Corp, 1977).

²³ H. H. Lowry, ed., Chemistry of Coal Utilization (John Wiley & Sons, Inc., 1945).

²⁴ Characteristics of American Coals in Relation to Their Conversion Into Clean Energy Fuels, Quarterly Technical Progress Report (Coal Research Section, Pennsylvania State University, 1976).

2 FINDINGS

Samples

Three types of DRDF and one type of coal were tested in this investigation (Table 1). Approximately 27 kg of California DRDF, paper cubes, and coal were analyzed, as well as 11 kg of National Center for Resource Recovery (NCRR) DRDF.

Upon collection, all samples were sealed in air-tight containers to inhibit changes in moisture content. Table 2 provides proximate and ultimate analyses and as-fired heating values of the samples. These data were provided either by the sample source or derived from other laboratory analyses.

Two of the DRDF samples analyzed were produced by mechanically processing mixed municipal-residential solid waste. The NCRR and California DRDF were manufactured by passing as-delivered solid waste through multiple shredding stages, separating magnetic metals, air classifying, and mechanically extruding the high-cellulose light feedstock in a California Pellet Mill. The paper cubes were manufactured by shredding and mechanically extruding highly homogeneous heavy paper stock such as magazines. While the NCRR and California DRDF contained noticeable impurities (i.e., small amounts of wood, plastic, metal, and grit), the paper cubes appeared to consist entirely of paper.

Table 1

List of Samples

<u>SAMPLE</u>	<u>SOURCE</u>
NCRR DRDF	National Center for Resource Recovery, Washington, DC
California DRDF	Vista Chemical and Fiber, Inc., Los Gatos, CA
Paper cubes	Papakube Corp., Los Angeles, CA
Coal	Low-volatile bituminous coal, Danville, IL

Table 2
Fuel Properties of Samples

SAMPLE	PROXIMATE ANALYSIS*				ULTIMATE ANALYSIS*				AS-FIRED HEATING VALUE		SOURCE	
	MOISTURE	VOLATILES	FIXED CARBON	ASH	CARBON	HYDROGEN	OXYGEN	NITROGEN	SULPHUR	ASH		kJ/kg
MCRR DRDF	14.1	57.4	12.3	16.3	37.9	6.0	38.0	1.9	--	16.2	13,607	Manufacturer
California DRDF	18.0	60.0	7.0	15.0	37.5	6.1	38.7	2.6	0.1	15.0	13,102	**
Paper Cubes	1.0	59.1	11.3	19.6	41.2	5.1	31.8	2.3	--	19.6	14,189	Manufacturer
Coal	12.0	40.2	39.1	8.6	62.8	5.9	17.4	1.0	4.3	8.6	26,702	**

* - Mean weight percent for five analyses

** - S. A. Hathaway and C. J. Dealy, Technology Evaluation of Army - Scale Waste-to-Energy Systems, Interim Report E-110/ADA042518 (U.S. Army Construction Engineering Laboratory, July 1977).

Ignition and Combustion Rates

Essential components of the experimental rig used in the investigation were an electrically heated, heavy-duty muffle furnace; a digital multimeter to display transformed temperature data sensed by ceramic thermocouples; and an on-line instrument train to measure oxygen, carbon monoxide, and carbon dioxide in the off-gases. Auxiliary equipment included a Wiley Laboratory Mill and Mettler model P11N analytical balance.

Ignition Rates

In the ignition time analyses, the furnace was preheated to the predetermined temperature, and an open platinum crucible containing 1 g of sample ground to 90 percent minus 1 mm was inserted into the chamber. Ignition was defined as the first appearance of visible flame. Early in the analyses it became apparent that no ignition of any sample could be expected at furnace temperatures equal to or less than 500°C within very lengthy residence times. Therefore, analyses were conducted at temperatures of 600°C and upward. Time to visible flame was recorded by stopwatch. Depending on the consistency of results, tests were repeated up to 10 times for furnace temperatures ranging from 600°C to 1000°C in increments of 100°C. All tests reported here were conducted at approximately 150 percent stoichiometric air.

Figures 1 and 2 illustrate the results of the ignition time tests. For convenience of illustration, the arithmetic mean ignition time for the three DRDF samples is compared to the as-determined ignition time of the coal sample. No attempt was made to cross-compare the ignition times of the DRDF samples.

Figure 1 shows the tendency of DRDF to ignite more rapidly than the coal over the entire range of temperatures. At 600°C, the time to DRDF ignition is about 12 times greater than for coal ignition. As indicated in Figure 1, DRDF ignites in the 500°C to 600°C temperature range, while the coal ignites in the 600°C to 700°C temperature range.

The ignition time curves for DRDF and coal shown in Figure 1 appeared to be nearly parallel in semi-logarithmic coordinates. Accordingly, a linear regression was made on the ratio of the arithmetic mean DRDF ignition time to that of coal as a function of temperature. The regression data shown in Figure 2 indicate the DRDF:coal ignition time ratio increases as temperature increases. The correlation coefficient of 0.964 was found to be significant at the 95 percent confidence level.

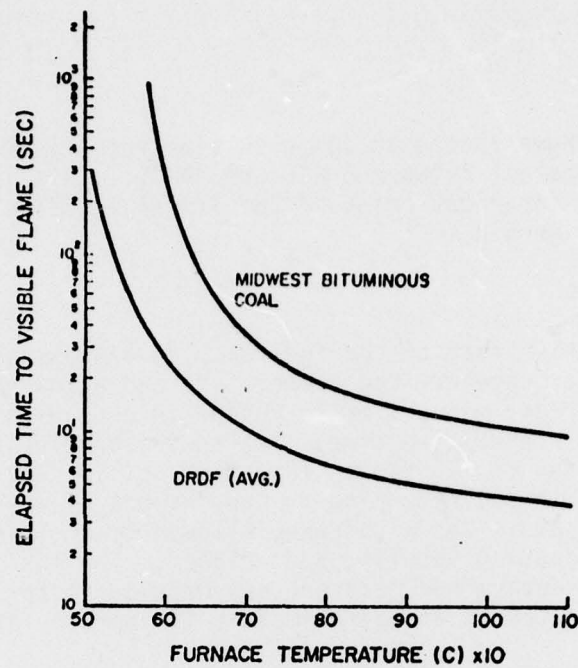


Figure 1. Time to ignition for coal and DRDF (mean).

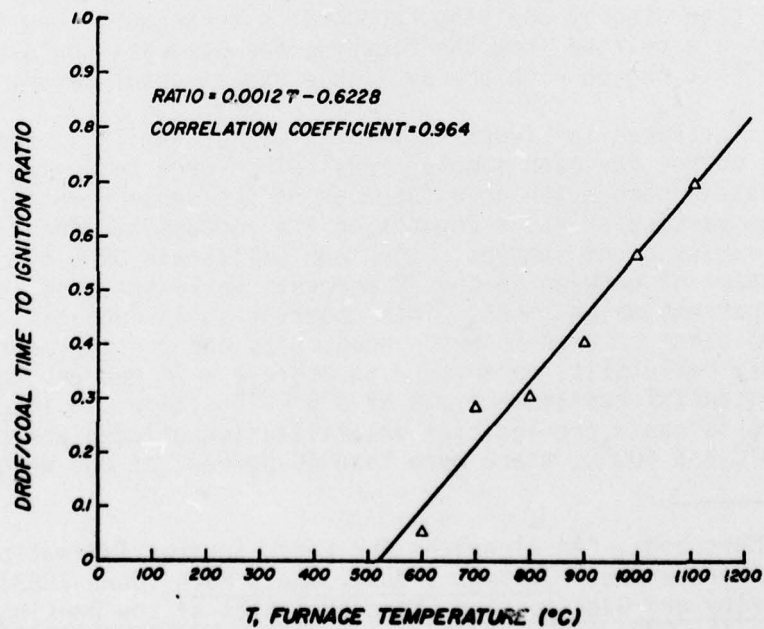


Figure 2. DRDF:coal ignition time ratio.

Figure 1 shows that each ignition time curve is temperature-asymptotic in the interval between 500°C and 700°C. This is also reflected by the abscissa intercept point of the linear ignition time ratio function shown in Figure 2.

Combustion Rates

The combustion rate of the fuel samples was assessed by preheating the furnace to a predetermined temperature and allowing 1 g of sample ground to 90 percent minus 1 mm to reside in a platinum crucible within the furnace for a specified time. Tests were carried out for times ranging from 5 sec to 115 sec in increments of 10 sec. Tests were repeated up to 10 times, depending on consistency of data. At the end of each test, the sample was withdrawn, allowed to cool in a controlled environment (desiccating vessel), and weighed. The loss in weight, adjusted by a pre-determined moisture evaporation factor, was recorded. The samples were tested at approximately 150 percent stoichiometric air.

Figures 3 through 6 illustrate results of the combustion rate analyses. Figure 7 displays the arithmetic mean rate of the DRDF samples. The rate curves in these figures were generated from up to 10 data points, using Marquardt's method for least-squares estimation of nonlinear parameters to minimize the squared differences between the actual and predicted dependent variable (e.g., weight loss) to within 0.01 percent.²⁵ The curves were plotted on a Calcomp plotter from the functions generated by applying Marquardt's technique. Low time weight loss rates are omitted from the figures, because data could not be collected in this region with the available experimental setup.

As illustrated in Figures 3 through 7, the family of temperature-dependent curves for each sample tends to converge to a single value of weight loss in combustion as a function of residence time in the furnace. The particular value depends on the combustible fraction of the fuel and varies among samples. NCRR and California DRDF tend to attain weight losses of between 68 and 72 percent, while the paper cubes attain up to 90 percent weight loss. This observation is compatible with results from other studies in which wood chips and pressed paper, both also highly cellulosic, were found to achieve a 74 percent weight loss after substantial residence times at 570°C.²⁶ These studies indicated that there is rapid pre-ignition volatilization of wood and paper between 300°C and 400°C, where more than 60 percent of the weight loss of

²⁵ D. W. Marquardt, "An Algorithm for Least-Squares Estimation of Non-linear Parameters," *J. Soc. Indust. Appl. Math* (June 1963).

²⁶ Reactivity and Gasification Characteristics of Low Ranking Coals and Potentially Reducing Waste Materials (Pittsburgh Energy Research Center Report PERC/RI-72/2, 1976).

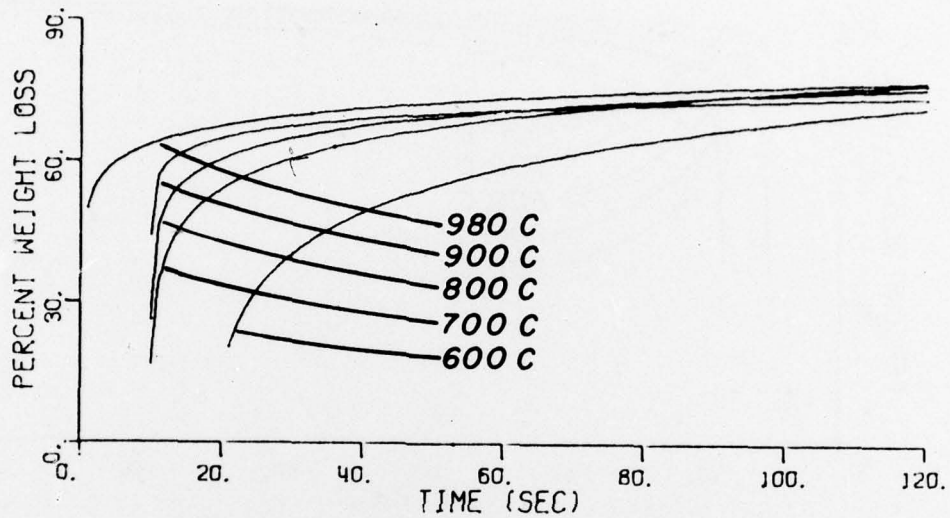


Figure 3. Combustion rate of NCRR DRDF.

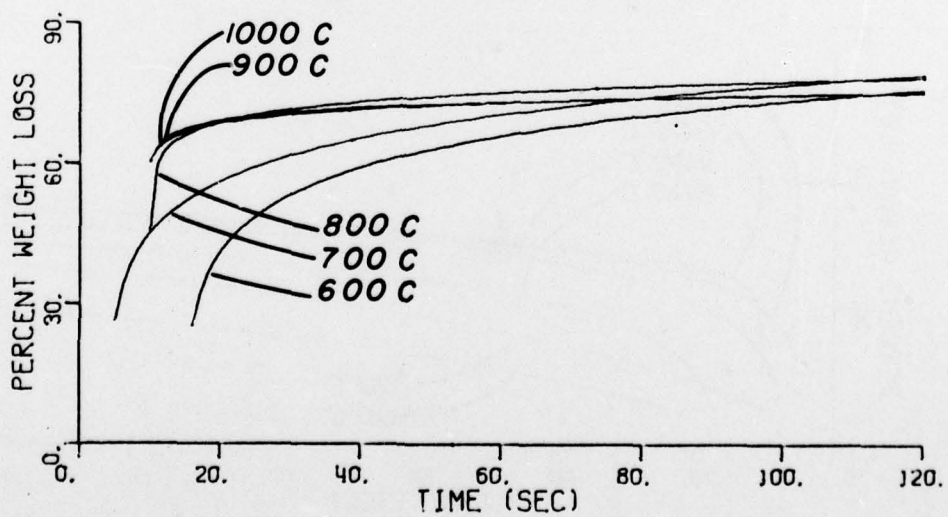


Figure 4. Combustion rate of California DRDF.

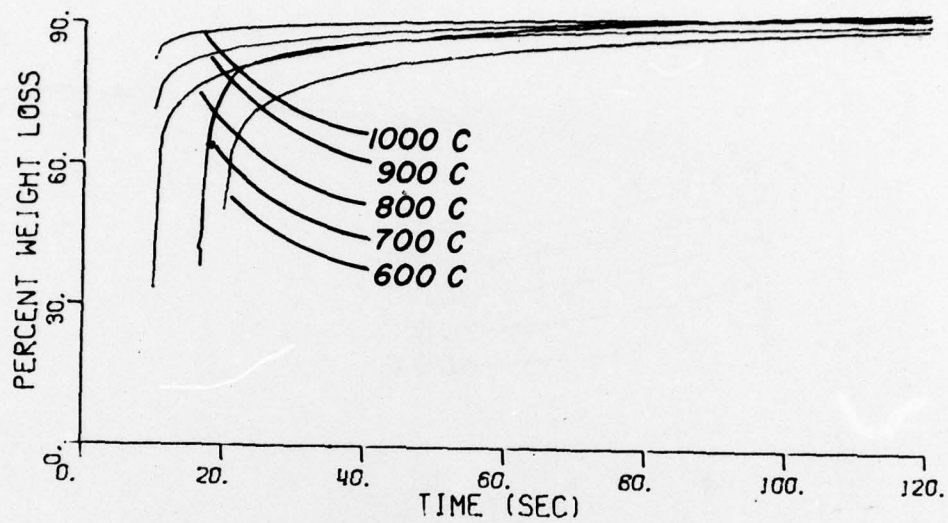


Figure 5. Combustion rate of paper cubes.

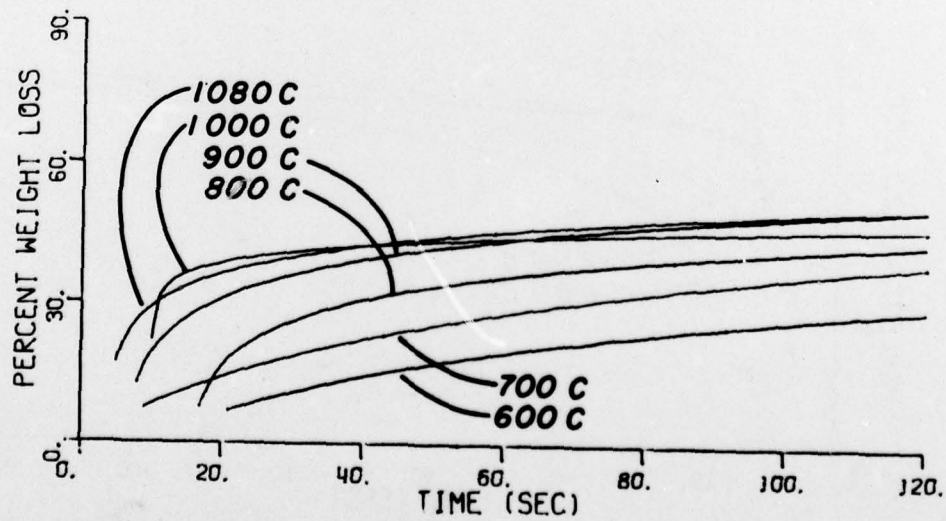


Figure 6. Combustion rate of Illinois bituminous coal.

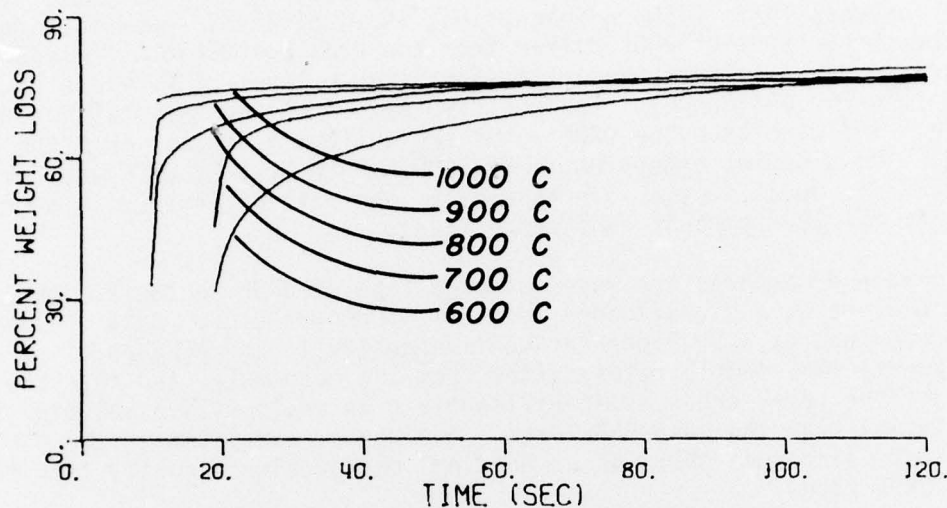


Figure 7. Mean DRDF combustion rate.

carbonaceous materials (due to loss of volatiles) occurs. Conversely, the coal tested here equilibrates at approximately 700°C. As shown in Figure 6, the combustion rate of coal is substantially lower than that of the DRDF evaluated.

Statistical Analyses

The paired, two-tailed Student's t-test was used to compare (1) the combustion rates of each type of DRDF both to the coal rate and to the arithmetic mean DRDF rate, (2) the mean DRDF rate to the coal rate, and (3) the NCRR and California DRDF rates both with each other and to the rate of the paper cubes.²⁷ Tests were conducted for each rate curve of each sample based on six data points from each curve. Rate data for the NCRR DRDF taken at 980°C (Figure 3) were adjusted to 1000°C by linear proportioning. In conducting the tests, the null hypothesis of mean equality was established, a significance level (α) chosen, the Student's t-statistic computed, and the corresponding probability of t (P_t) found. The value of P_t was then compared to the value of α and the null hypothesis either retained or rejected.

²⁷ Statistical Package for the Social Sciences (McGraw-Hill, Inc., 1975).

Table 3 compares the combustion rates of the three types of DRDF to that of coal, as provided by results of the statistical analysis. These data indicate that, with one exception, the individual combustion rates of the three types of DRDF differ from the coal combustion rate over the entire range of temperatures at a significance level of 0.001 (e.g., 99.9 percent confidence). The positive values of the t-statistic in Table 3 indicate that the DRDF rates are uniformly greater than the coal rate. The singular exception is the 600°C rate of NCRR DRDF and coal, where P_t is equal to (α) . In this case, the rate difference is significant at the 99.8 percent confidence level.

Table 4 compares the rates of each type of DRDF to the arithmetic mean DRDF rate; a significance level of 0.001 was used. Data in Table 4 indicate that at a 99.9 percent confidence level, the NCRR and California DRDF sample rates differ from the mean rate, and that the rate of the paper cubes is significantly greater (positive value of t-statistic) than the mean DRDF rate. A singular exception is the 800°C rate for California DRDF, which does not differ significantly from the mean DRDF rate.

Table 5 compares the mean DRDF rate to the rate of coal. The coal rate is significantly different from the mean DRDF rate at the 99.9 percent confidence level. The positive sign of the t-statistic indicates that it is a uniformly lesser rate.

Table 6 compares the rates of NCRR and California DRDF. At a 99.9 percent confidence level, the rates can be considered the same. However, this is not the case when the rates of NCRR and California DRDF are compared to the rate of the paper cubes. The data shown in Table 7 indicate that, at a 99.5 percent confidence level, the paper cubes have a significantly greater rate over all temperatures at which testing was conducted, as shown by values of P and the negative sign of the t-statistics. These differences might be attributable to the high paper homogeneity of the paper cubes as compared to the relatively impure NCRR and California DRDF samples.

Table 3

Values of t and P_t From Comparing Rates of Three
DRDF Types to Coal Rate

<u>TEMPERATURE ($^{\circ}\text{C}$)</u>	<u>SAMPLE</u>	<u>t</u>	<u>P_t</u>
600	NCRR DRDF	6.44	0.001
	California DRDF	19.37	0.000
	Paper Cubes	14.38	0.000
700	NCRR DRDF	77.30	0.000
	California DRDF	81.39	0.000
	Paper Cubes	33.37	0.000
800	NCRR DRDF	27.06	0.000
	California DRDF	19.65	0.000
	Paper Cubes	55.07	0.000
900	NCRR DRDF	41.44	0.000
	California DRDF	28.74	0.000
	Paper Cubes	53.75	0.000
1000	NCRR DRDF	66.07	0.000
	California DRDF	33.30	0.000
	Paper Cubes	38.54	0.000

Table 4

Values of t and P_t From Comparing Rates of Three
DRDF Types to Mean DRDF Rate

<u>TEMPERATURE ($^{\circ}\text{C}$)</u>	<u>SAMPLE</u>	<u>t</u>	<u>P_t</u>
600	NCRR DRDF	-3.07	0.028
	California DRDF	-0.38	0.721
	Paper Cubes	11.65	0.000
700	NCRR DRDF	0.00	1.000
	California DRDF	0.53	0.618
	Paper Cubes	13.70	0.000
800	NCRR DRDF	-1.20	0.286
	California DRDF	8.00	0.000
	Paper Cubes	10.55	0.000
900	NCRR DRDF	-2.28	0.071
	California DRDF	-1.94	0.110
	Paper Cubes	18.58	0.000
1000	NCRR DRDF	0.11	0.920
	California DRDF	-1.57	0.178
	Paper Cubes	27.12	0.000

Table 5

Values of t and P_t From Comparing Mean DRDF Rate to Coal Rate

<u>TEMPERATURE ($^{\circ}\text{C}$)</u>	<u>SAMPLE</u>	<u>t</u>	<u>P_t</u>
600	DRDF Avg.	15.31	0.000
700	DRDF Avg.	26.39	0.000
800	DRDF Avg.	17.04	0.000
900	DRDF Avg.	20.44	0.000
1000	DRDF Avg.	18.03	0.000

Table 6

Values of t and P_t From Comparing Rate of NCRR DRDF to Rate of California DRDF

<u>TEMPERATURES ($^{\circ}\text{C}$)</u>	<u>SAMPLE</u>	<u>t</u>	<u>P_t</u>
600	NCRR DRDF	-2.62	0.047
700	NCRR DRDF	-3.16	0.025
800	NCRR DRDF	-4.47	0.007
900	NCRR DRDF	-1.94	0.110
1000	NCRR DRDF	2.19	0.080

Table 7

Values of t and P_t From Comparing Rates of NCRR and California DRDF
to Rate of Paper Cubes

<u>TEMPERATURES ($^{\circ}\text{C}$)</u>	<u>SAMPLE</u>	<u>t</u>	<u>P_t</u>
600	NCRR DRDF	-10.63	0.000
	California DRDF	-7.29	0.001
700	NCRR DRDF	-10.86	0.000
	California DRDF	-9.46	0.000
800	NCRR DRDF	-20.76	0.000
	California DRDF	-9.68	0.000
900	NCRR DRDF	-49.30	0.000
	California DRDF	-41.94	0.000
1000	NCRR DRDF	-15.61	0.000
	California DRDF	-45.26	0.000

3 CONCLUSIONS AND RECOMMENDATIONS

The general time- and temperature-related ignition characteristics of DRDF are different from those of coal. At 600°C, the time to DRDF ignition is 12 times sooner than to coal ignition. The temperature required for coal ignition at a given furnace residence time is greater than that needed for DRDF ignition.

The DRDF:coal time to ignition ratio can be expressed as a linear function of temperature.

For the samples evaluated, the combustion rates of DRDF are statistically significantly greater than the combustion rate of coal in the temperature range from 600°C to 1000°C and at furnace residence times ranging up to 120 sec. This difference is significant at a 99.9 percent confidence level.

DRDF produced from mechanically processed mixed solid waste has a lower combustion rate than that produced from highly homogeneous paper feedstock. This difference is significant at a 99.5 percent confidence level. In either case, the rates of DRDF are generally significantly greater than the rate of coal.

It is recommended that data and information presented in this report be used (1) in the design of experiments cofiring DRDF and coal mixtures in military-scale central heating and power plants, and (2) in the techno-economic assessment of boiler modification for using DRDF as a supplement to coal.

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